# Asteroseismology of B stars with MESA

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# Outline

- What is MESA (and GYRE)?
- Some examples of MESA results for B stars

  with Pieter Degroote and «the best students» from the MESA summer school 2013
- Asteroseismology of 15 CMa (very preliminary)

  with Maryline Briquet and Sophie Saesen

# What is MESA ?

**M**odules for **E**xperiments in **S**tellar **A**strophysics

MESA star: 1D stellar evolution code

**Bill Paxton**

- Open Source
- Independent modules
- Up-to-date, flexible
- Constantly evolving to include latest macro- and microphysics
- Performance: use of parallelism, multi-core architectures
- Wide applications in stellar evolution

mesa.sourceforge.net

MESA Council
Bill Paxton
Lars Bildsten
Aaron Dotter
Falk Herwig
Frank Timmes
Ed Brown
Rich Townsend
Matteo Cantiello

# What is MESA ?

## Well documented ➨ MESA instrument papers:

- **Paper I**: B. Paxton, L. Bildsten, A. Dotter, F. Herwig, P. Lesaffre, F. Timmes, ApJS 192, 2011
- **Paper II**: B.Paxton, M. Cantiello, P. Arras, L. Bildsten, E. Brown, A. Dotter, C. Mankovich, M.H. Montgomery, D. Stello, F. Timmes, R. Townsend, APJS 208, 2013

## MESA Forum:
mesastar.org

## Mailing list:
mesa-users

## MESA SDK (Software Development Kit)
Rich Townsend

# What can MESA do?

Everything a 1D stellar evolution code can do...

see instrument papers

MESA is constantly checked

- internally (consistency, accuracy, predictibility)
- externally:
  - compared with other codes (when possible)
  - compared to reproducible evidence

# What can MESA do?

Flexible: Possible to access all the variables used during the evolution to perform extra computations (using run_star_extras.f)

Example from the MESA summer school 2013:

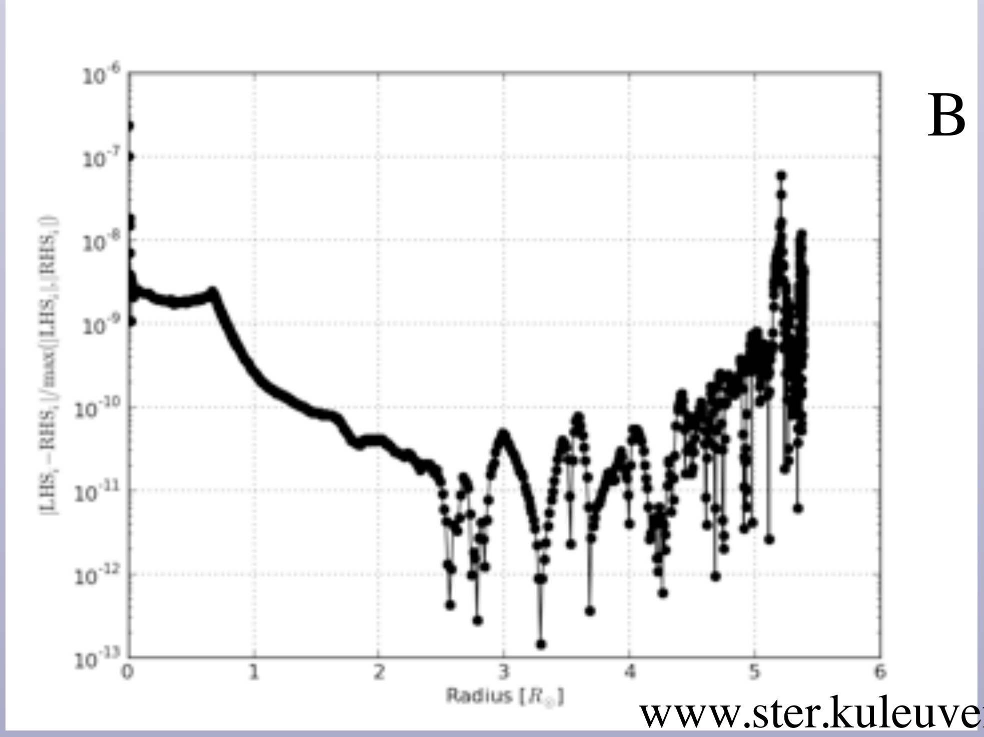
Verify that the MESA models are in hydrostatic equilibrium

(mesastar.org/documentation/mesa-summer-school-2013/asteroseismology-of-b-stars-with-mesa)

$$\frac{dP(r)}{dr} = -\rho(r) g(r)$$

$$2\frac{P_{i-1} - P_i}{dm_{i-1} + dm_i} = -\frac{Gm_i}{4\pi r_i^4}$$

$$q_i = \frac{|\mathrm{LHS}_i - \mathrm{RHS}_i|}{\max(|\mathrm{LHS}_i|, |\mathrm{RHS}_i|)}$$




B star MS model

www.ster.kuleuven.be/~pieterd/mesa/

# Using MESA

- ✔ Set up the INLIST
- ✔ Customize MESA
- ✔ Run MESA

# MESA and Asteroseismology

Asteroseismology:

Use observed stellar pulsations properties (frequencies, mode identification, mode amplitudes,...) to gain insight about the stellar interior structure

Stellar evolution code

+

Stellar oscillation code

# MESA and Asteroseismology

MESA profiles can be fed into pulsation codes such as ADIPLS

MESA is now coupled to GYRE
➥ much simpler

# MESA and Asteroseismology

## GYRE

Stellar oscillation code

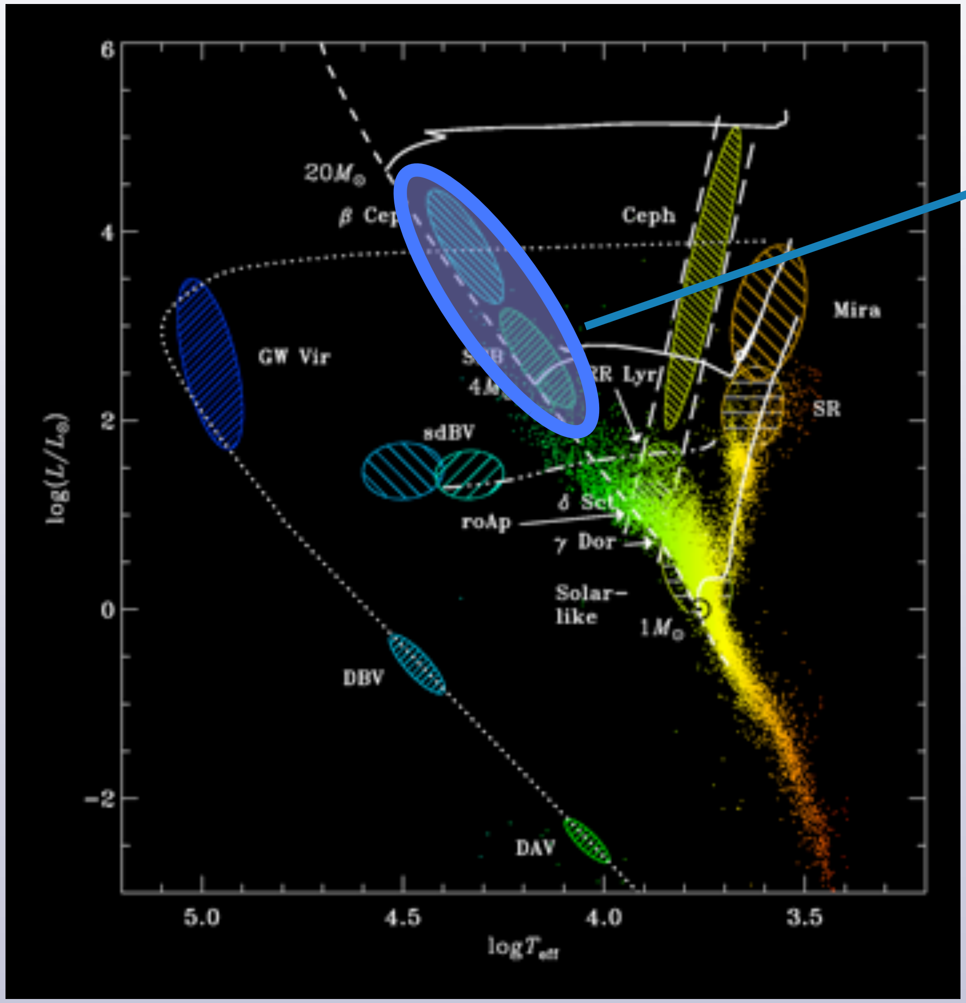
Rich Townsend

- Open Source
- Adiabatic and Non-adiabatic pulsations
- Efficient use of multi-cores architectures

bitbucket.org/rhdtownsend/gyre/wiki/home

**Paper**: Townsend & Teitler MNRAS 435, 2013

# Asteroseismology of Main Sequence B stars




users-phys.au.dk/jcd/HELAS/puls_HR/

log $T_{eff}$ ~ 4.1 - 4.5

log $L/L_\odot$ ~ 2 - 4

$M/M_\odot$ ~ 4 - 20

Multiperiodic pulsators:

- low-order p, g, mixed modes (β Cephei)
  periods of a few hours
- high-order g modes (SPB)
  periods 0.5 - 5 days

Long-lived modes

$\kappa$ mechanism in Fe opacity bump

➪ cf. Coralie Neiner's talk

# Asteroseismology of Main Sequence B stars

pressure (or acoustic) waves: frequency related to sound speed

$$\nu \propto \frac{c}{R} \propto \sqrt{\frac{M}{R^3}} \propto \sqrt{\rho}$$

⇒ info about the mean density

gravity modes: frequency related to the BV (buoyancy) frequency

$$N^2 = -\frac{g}{r}\left(\frac{1}{\Gamma_1}\frac{d\ln p}{d\ln r} - \frac{d\ln \rho}{d\ln r}\right) \approx \frac{\rho g^2}{p}(\nabla_{ad} - \nabla + \nabla_{\mu})$$

⇒ info about T and μ gradients at core boundary

# Asteroseismology of Main Sequence B stars

B stars have a simple internal structure:
convective core + radiative envelope

Some of the remaining open questions:

Size of the convective core; influence of mixing
mixing mechanisms
internal differential rotation
excitation of the observed modes (low frequencies in hybrids)
B pulsators in LMC and SMC

# Asteroseismology of Main Sequence B stars

Modularity of MESA
➜ simple to test different physics ingredients

- different compositions
- different opacity tables
- different treatments of the convection
- different mixing mechanisms and/or prescriptions
- effects of the rotation (as modeled in this 1D code)
- ....

# Asteroseismology of Main Sequence B stars

examples from MESA summer school 2013:

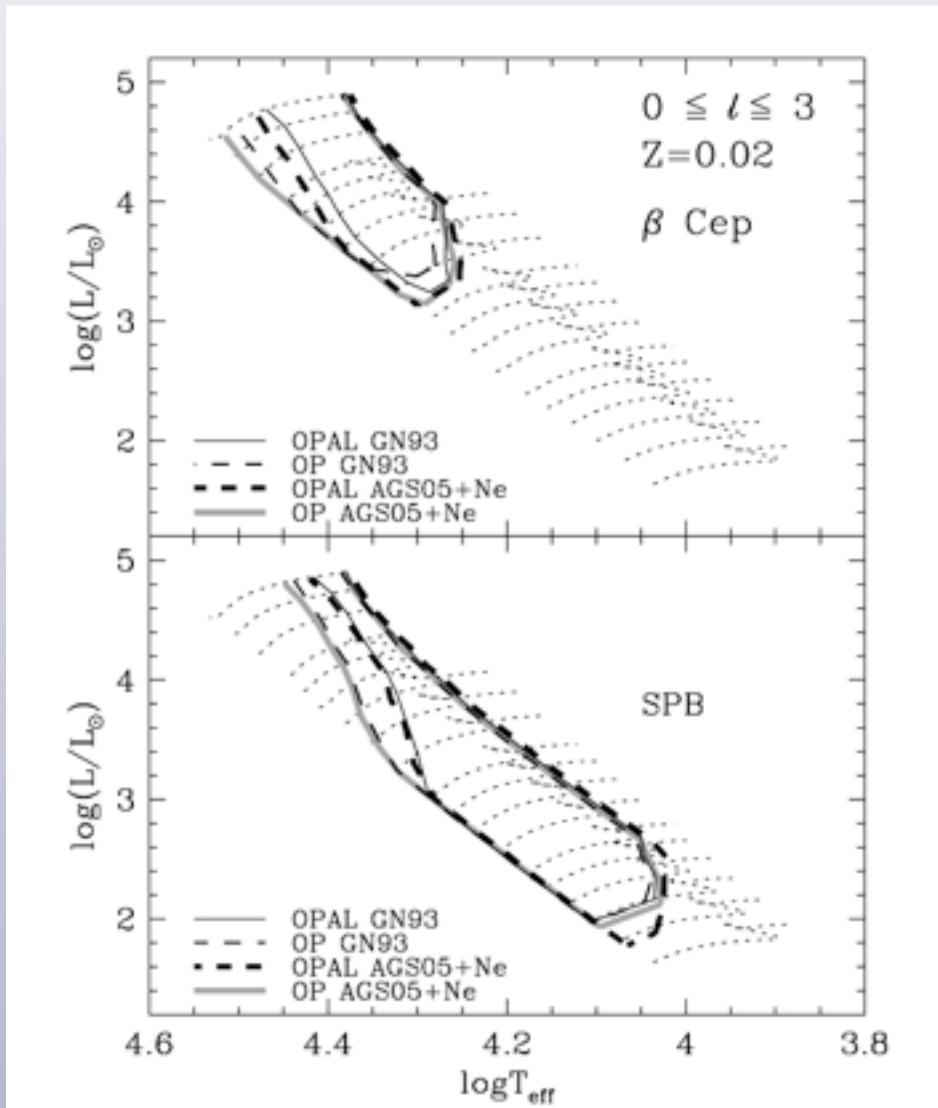
(see also mesastar.org)

Ex. 1: The β Cephei Instability Strip

Ex. 2: High-order gravity modes period spacings in SPBs

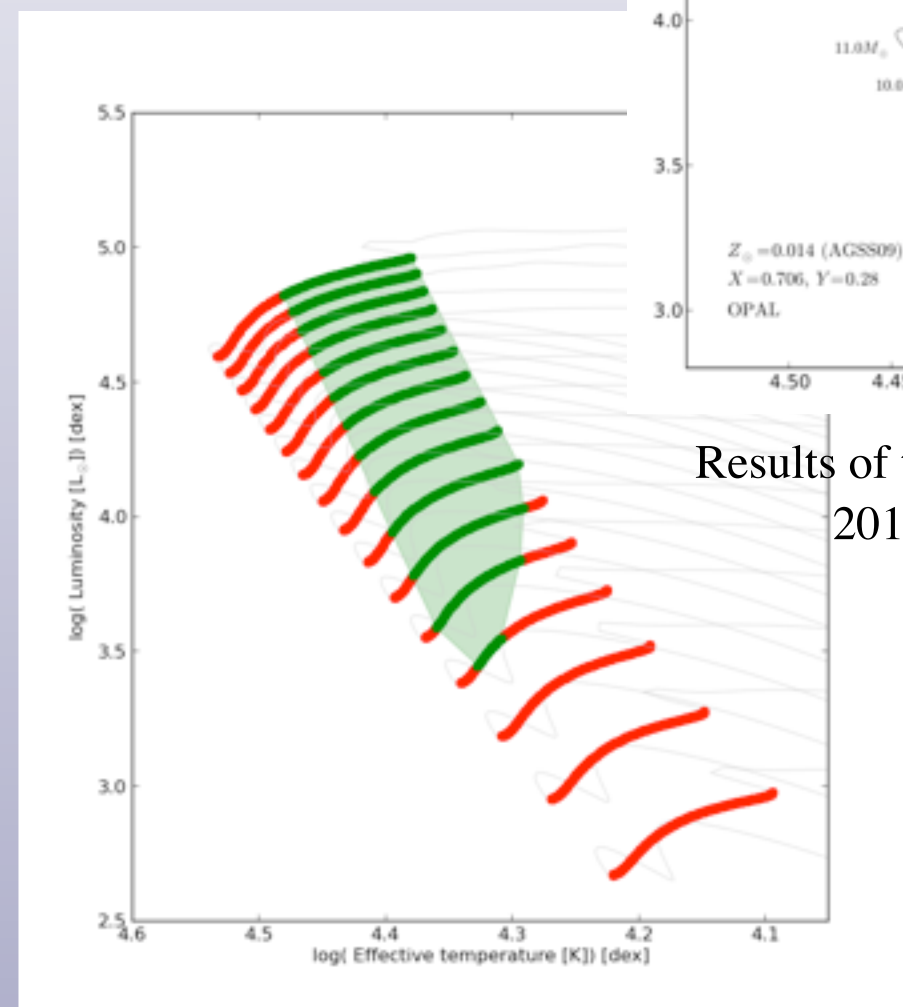
# Asteroseismology of Main Sequence B stars

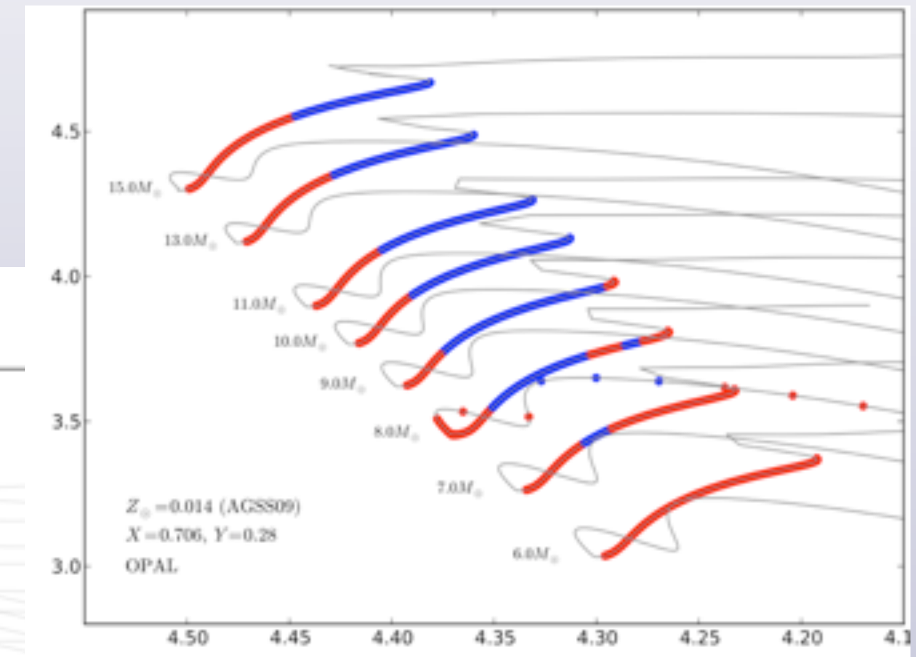
## Example: Probing the β Cephei Instability Strip




Miglio et al. 2007 CLES

**MESA**




Results of the best student team during the 2013 MESA summer school

www.ster.kuleuven.be/~pieterd/mesa/

# Asteroseismology of Main Sequence B stars

Example: High-order gravity modes period spacings

ΔP is uniform in the asymptotic limit ... but:

$$\Delta P = P_{n,l} - P_{n-1,l} = \frac{2\pi^2}{\sqrt{l(l+1)}} \frac{1}{\int_{r_1}^{r_2} \frac{N(r)}{r} dr}$$

receding core :

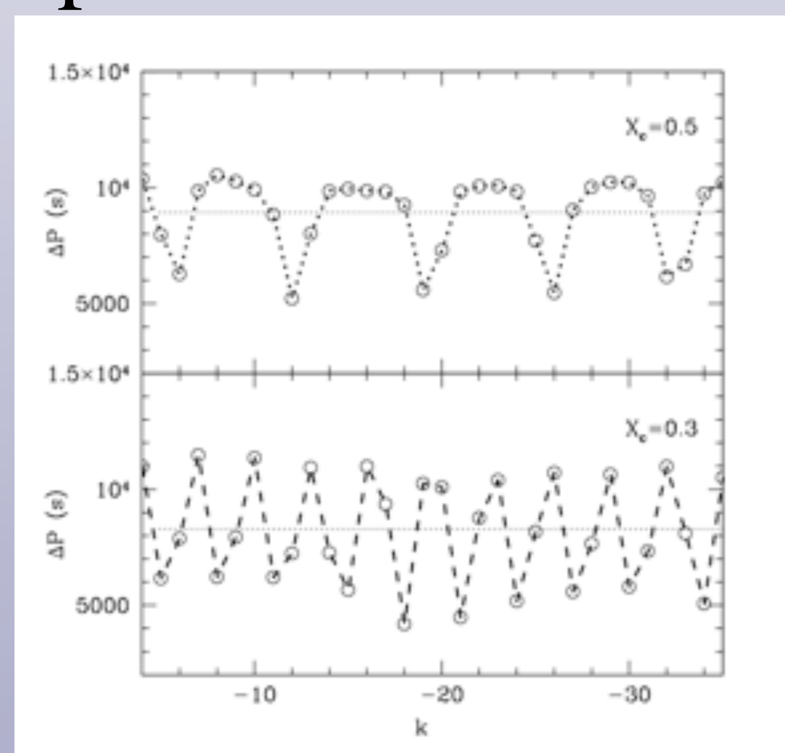
➔ ∇μ at core boundary

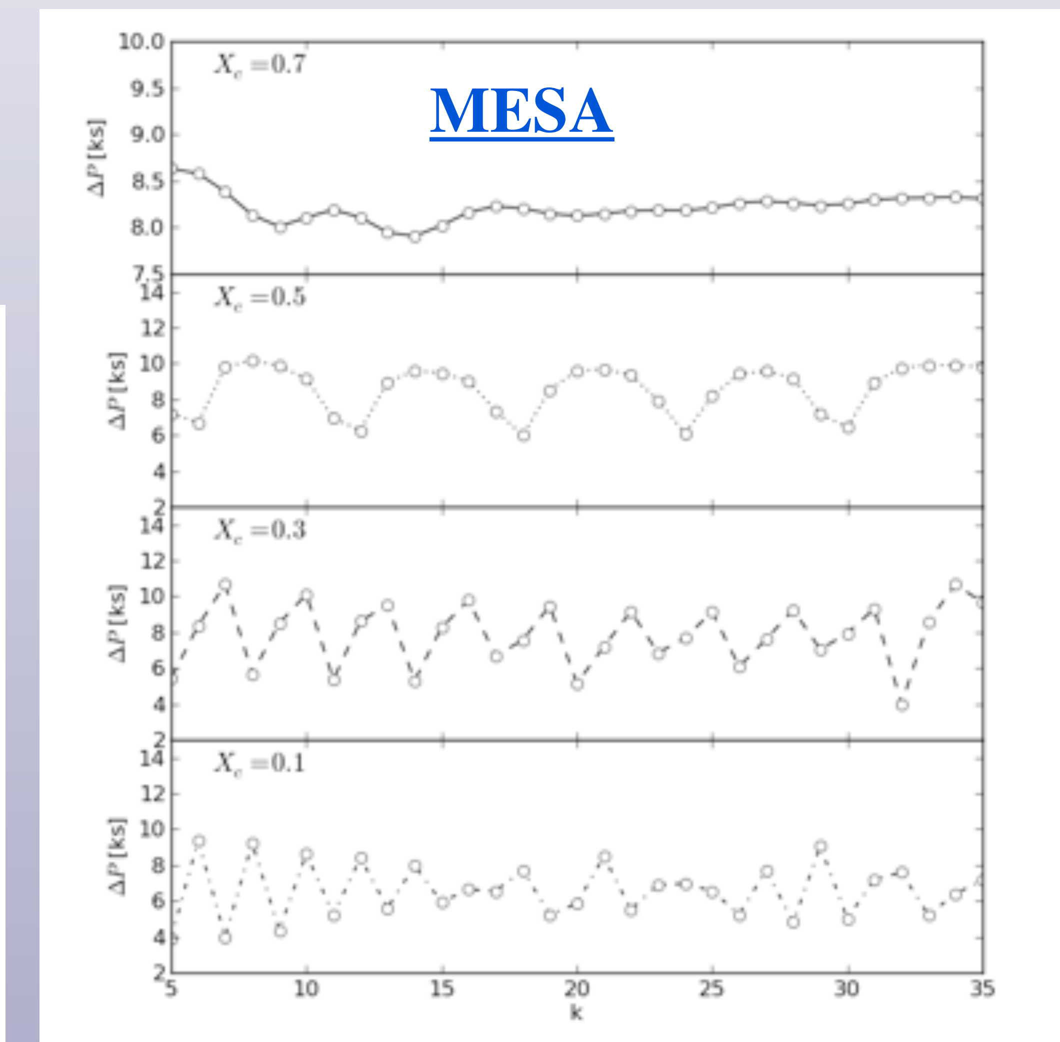
➔ sharp feature in BV frequency

➔ sinusoidal component in ΔP

Signature of evolutionary stage

Information about the mixing at core boundary



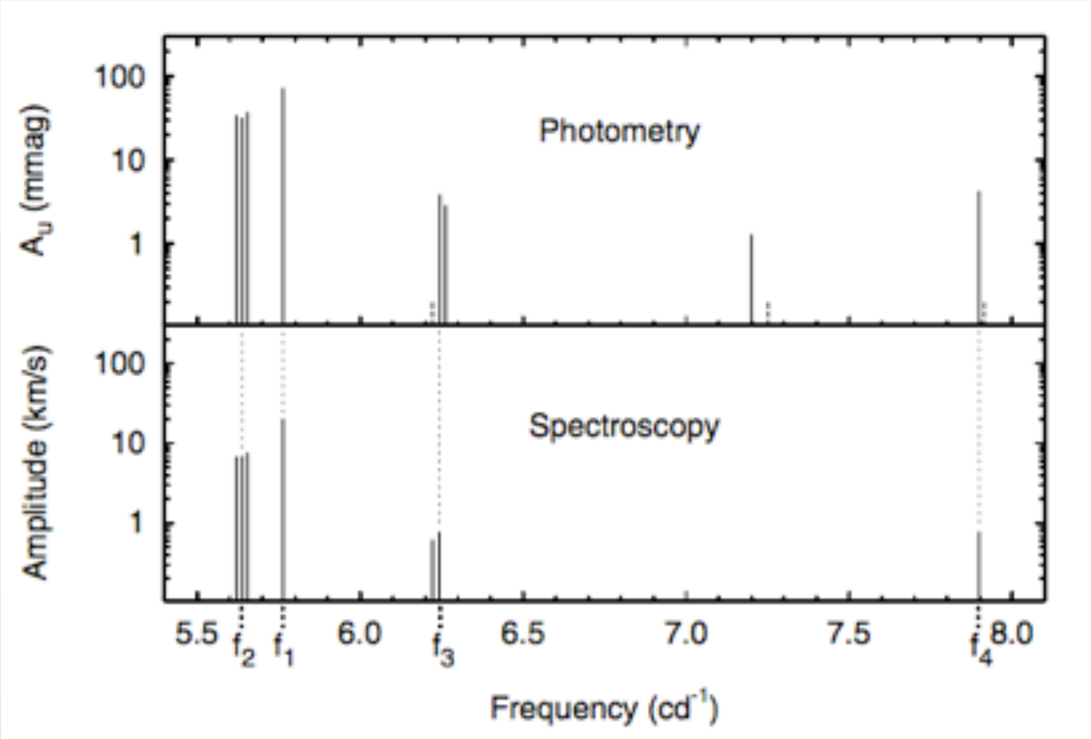

Miglio et al. CLES

www.ster.kuleuven.be/~pieterd/mesa/

# Asteroseismology of β Cephei stars

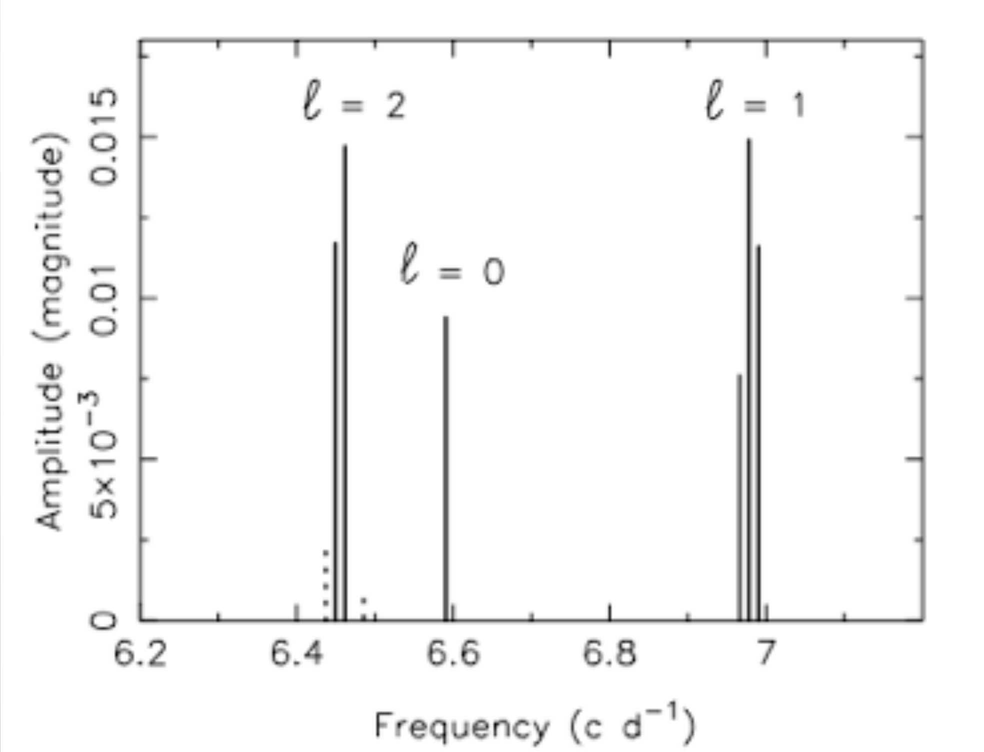
## Sparse spectrum of p modes

ν Eridani




Ausseloos et al. 2004

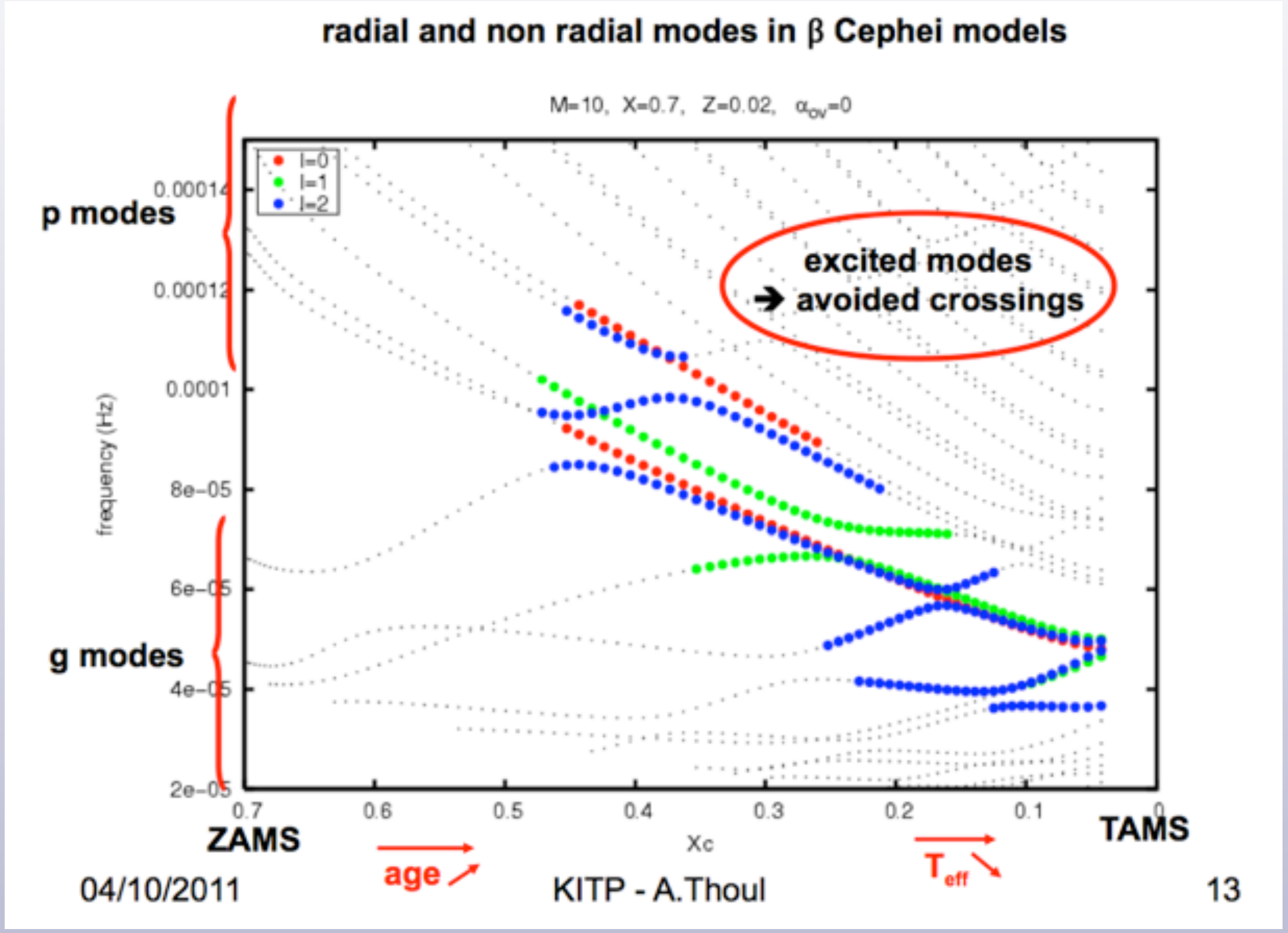
HD129929




Aerts et al. 2004

Fit individual modes ⇒ age, $T_{eff}$, log g, Z, M, R, ov

# Asteroseismology of β Cephei stars



# Asteroseismology of the $\beta$ Cephei star 15 CMa

See talk by Sophie Saesen

| | | |
|---|---|---|
| $f_1$=5.1831 $d^{-1}$ | l=0 | m=0 |
| $f_2$=5.4187 $d^{-1}$ | l=1,2,3 | m=0 |
| $f_3$=5.3085 $d^{-1}$ | l=3,4 | \|m\|=1 or 2 |
| $f_4$=5.5212 $d^{-1}$ | l=1,2,3 | $m > 0$ |

Very preliminary modeling!

# Asteroseismology of the β Cephei star 15 CMa

## Stellar models: use MESA

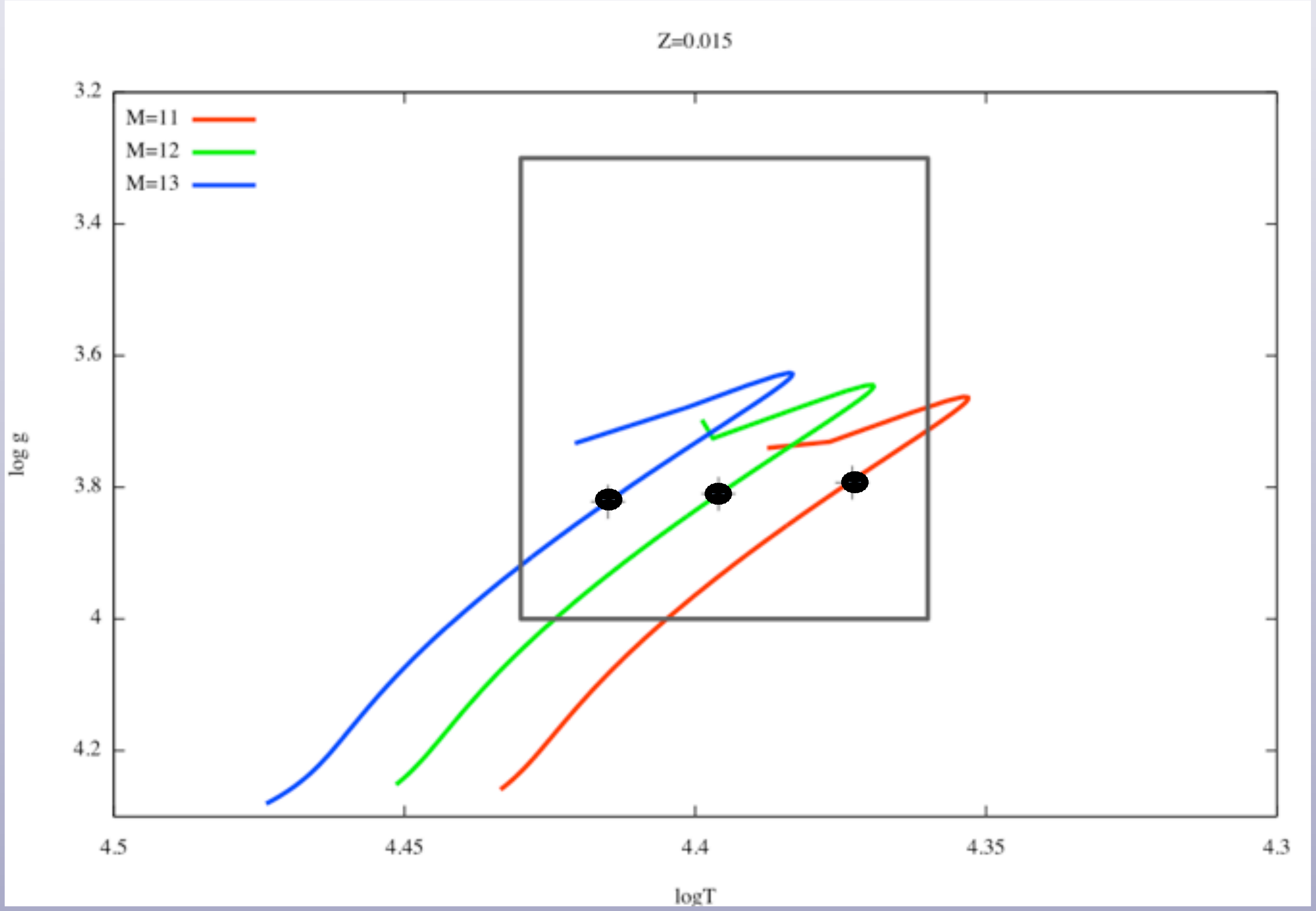
The ingredients for the inlist:

- **chemical composition** → AGS2009
- network of nuclear reactions
- **opacity table** → OPAL
- equation of state
- photosphere
- treatment of convection
- **overshooting** → Diffusive overshooting f= 0 to 0.016 (A&A, 360, 952-968 (2000))
- other mixing
- **mass** → $M=10$ to $13\ M_\odot$
- **metallicity** → $Z=0.01$ to $0.02$

# Asteroseismology of the β Cephei star 15 CMa

**Evolutionary tracks**

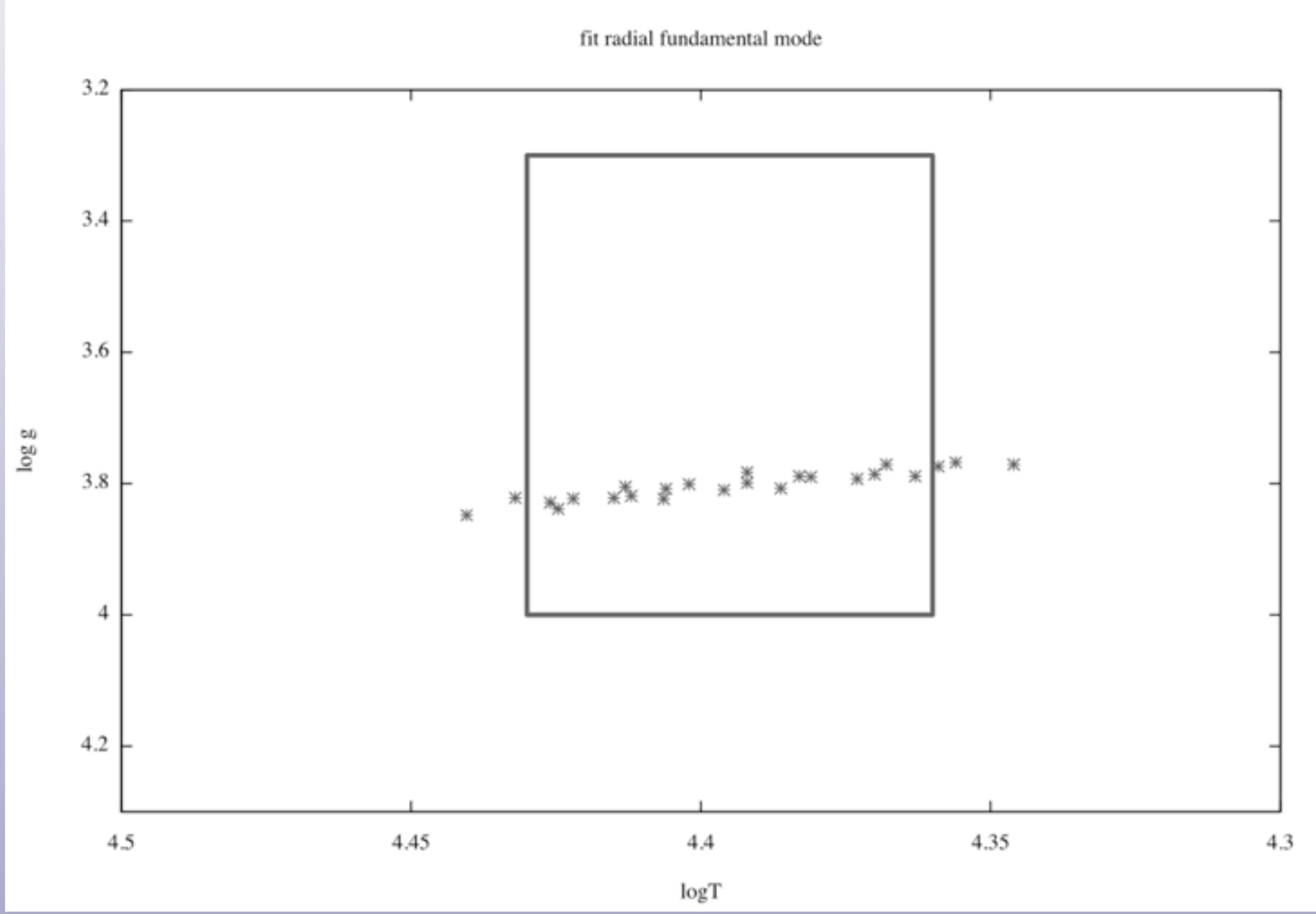
fit radial fundamental mode frequency ⇒ fix the age (evolutionary stage) of the star



# Asteroseismology of the β Cephei star 15 CMa

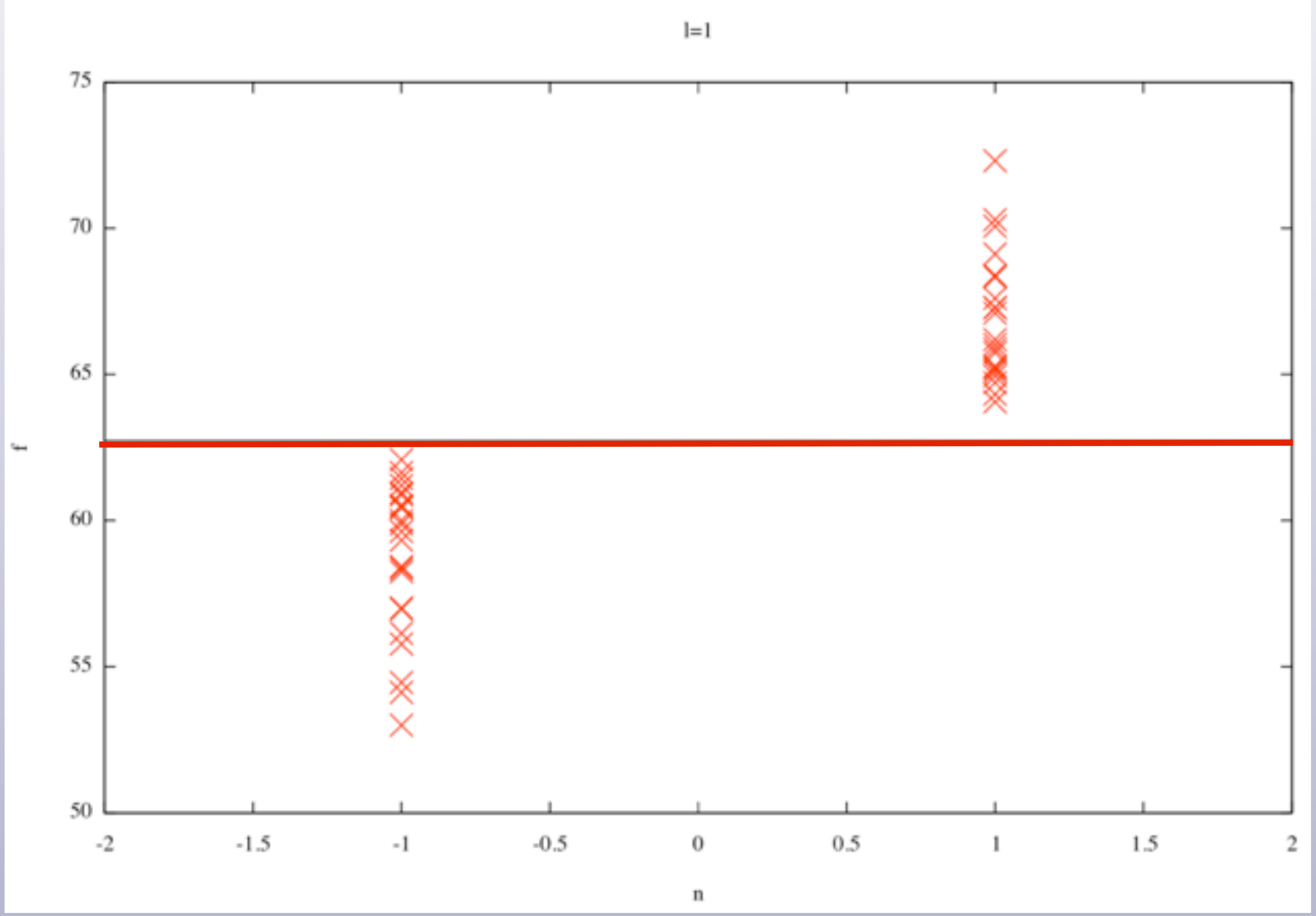
Results for all calculated models

fit radial mode frequency ⟺ fix log g

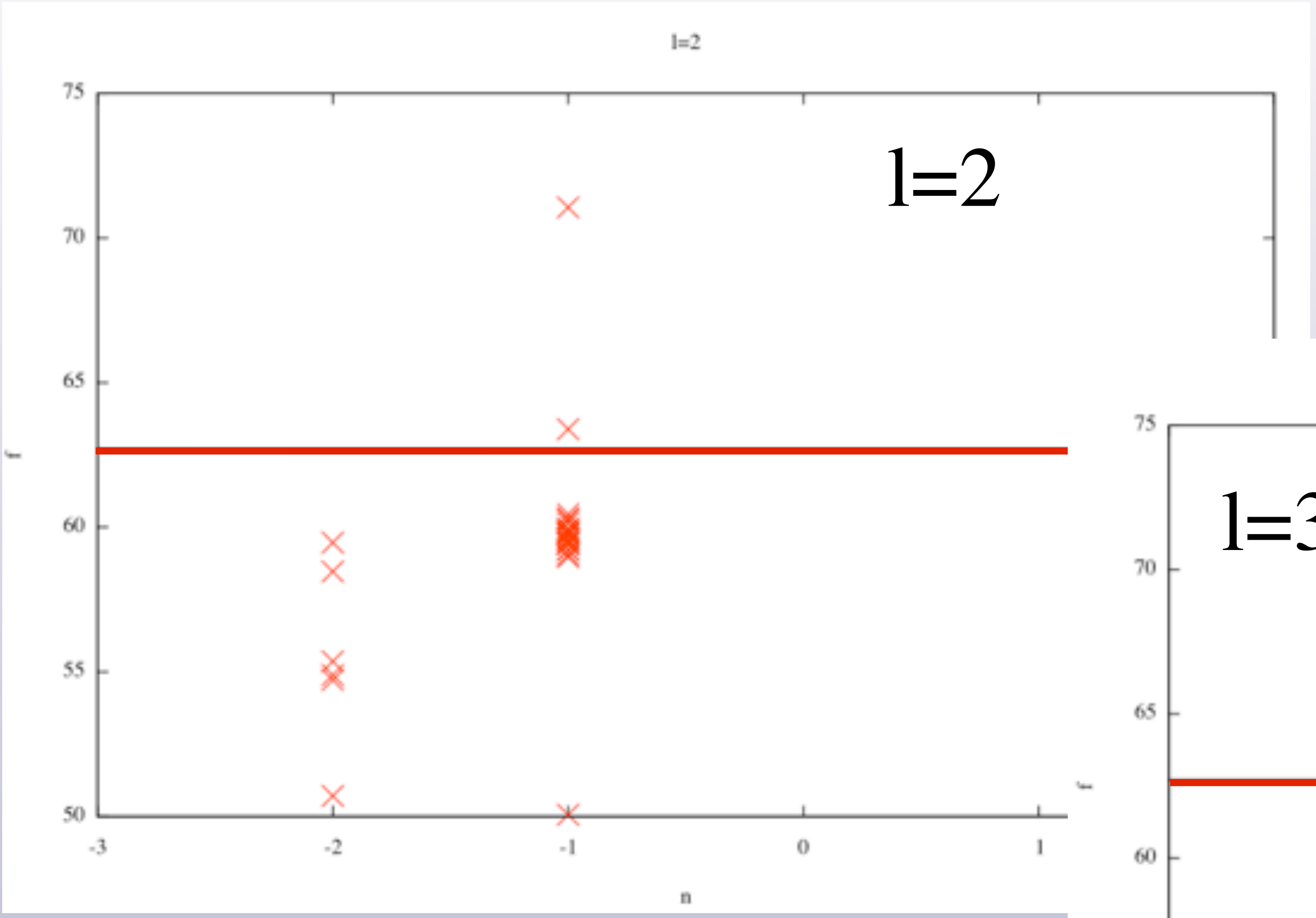


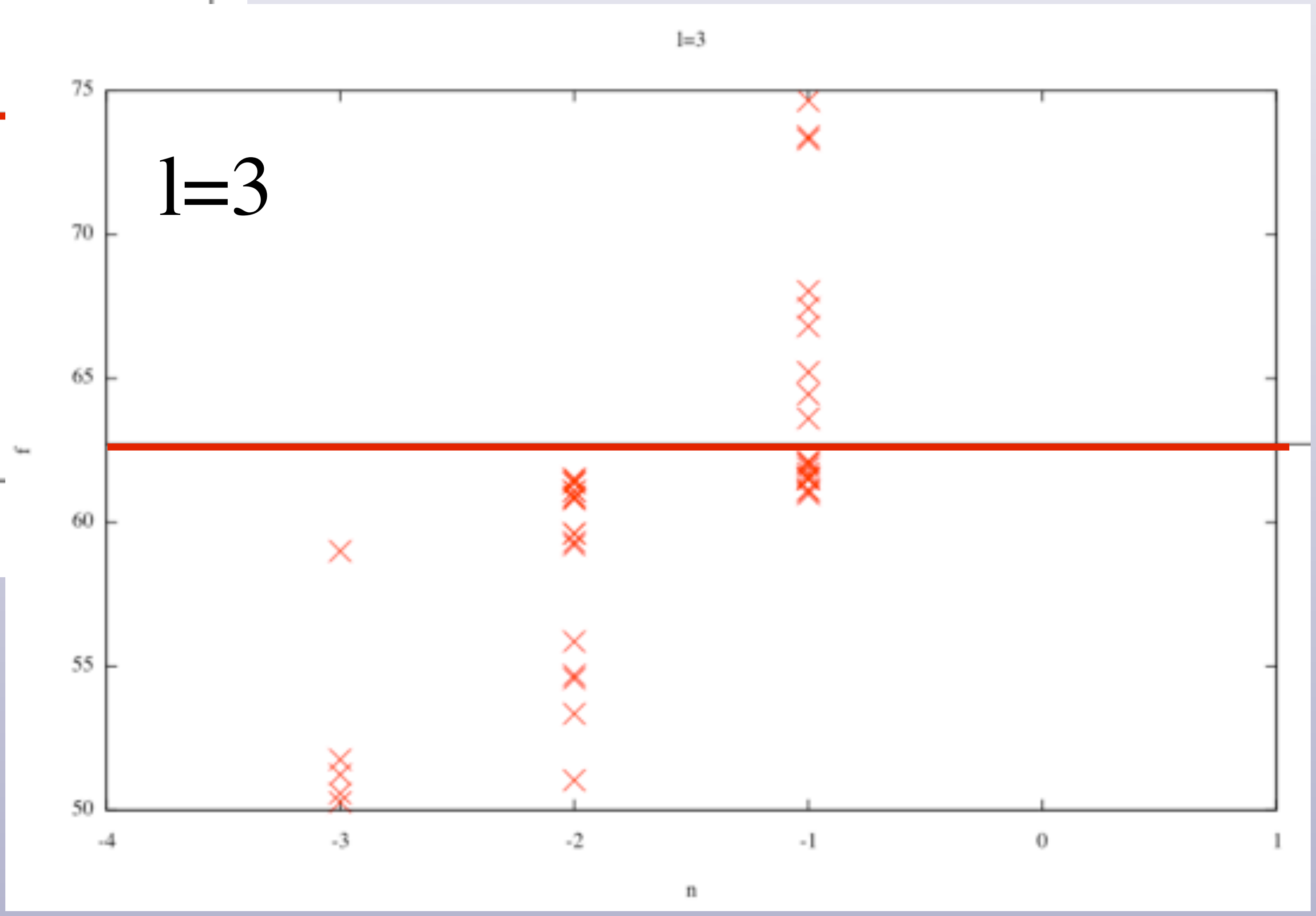
# Asteroseismology of the β Cephei star 15 CMa

Impossible to fit the second axisymmetric mode with l=1



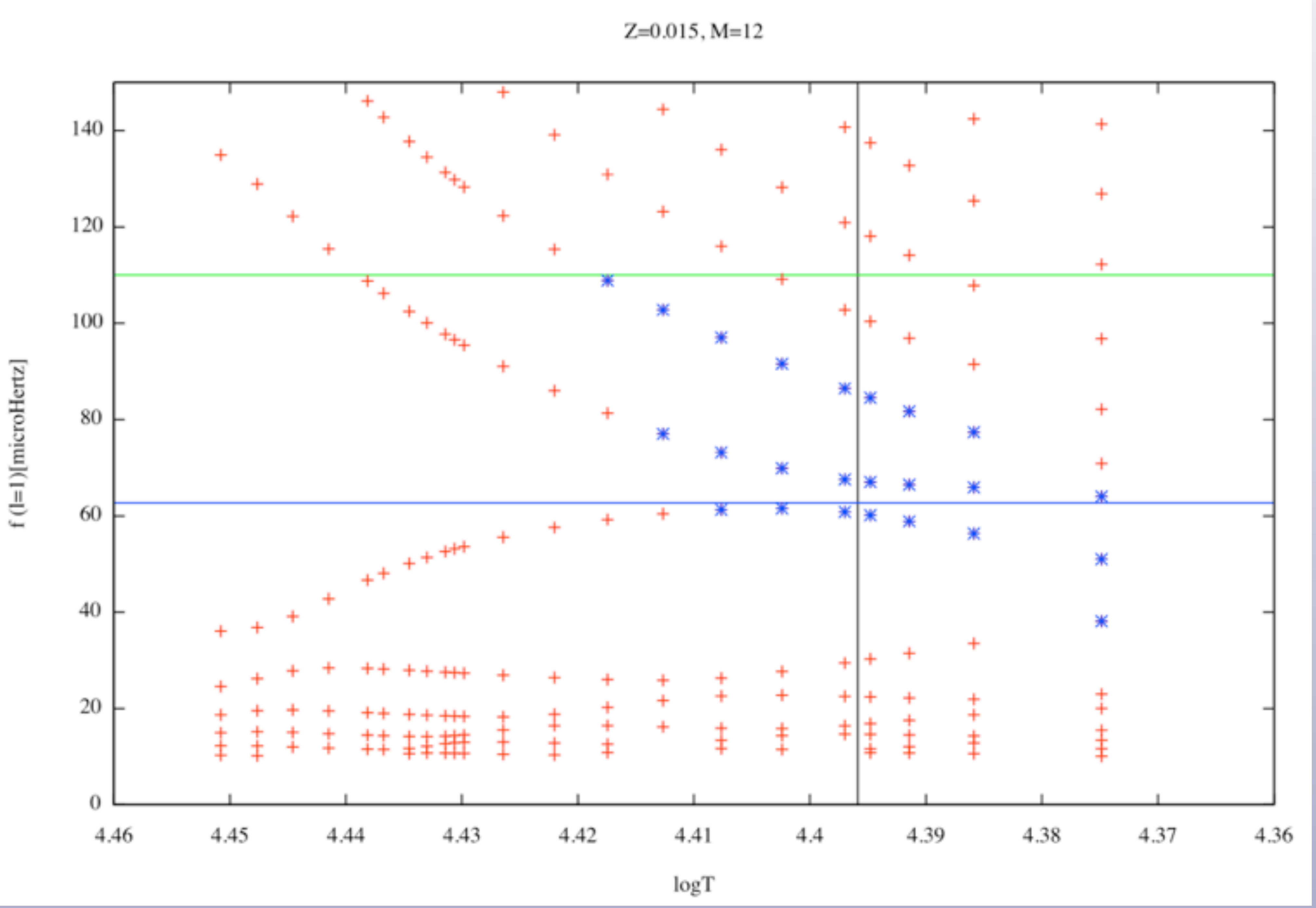
# Asteroseismology of the β Cephei star 15 CMa



# Asteroseismology of the β Cephei star 15 CMa

## mode excitation



# Asteroseismology of the $\beta$ Cephei star 15 CMa

Work in progress....!

WAITING FOR :

- progress in identification
- information on the rotation velocity

TO DO LIST :

- Improve modeling
- Look at the mode excitation
- Study the impact of composition and opacities

Thank you!